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Working Group 2 Summary: Space Charge Effects in Bending Systems

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WORKING GROUP 2 SUMMARY: SPACE CHARGE EFFECTS IN BENDING SYSTEMS

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Participants in Working Group 2 included: Y. Batygin, C. Bohn, B. Carlsten, J. Ellison, P. Emma, Z. Huang, A. Kabel, R. Kishek, R. Li, P. Musumeci, S. Nagaitsev, J. Qiang, M. Reiser, A. Ruggerio, R. Warnock, and M. Zeitlin.

1 Charge to the Working Group

At the start of the Workshop, we asked the Working Group 2 participants to concentrate on three basic goals: (1) survey the status of how comprehensively the physics concerning space-charge effects in bends is understood and how complete is the available ensemble of analytic and computational tools; (2) guided by data from experiments and operational experience, identify sources of, and cures for, beam degradation; and (3) review space-charge physics in rings and the limitations it introduces. As the Workshop unfolded, the third goal naturally folded into the other two goals, and these goals, we believe, were fulfilled in that the Working Group was able to compile an end product consisting of a set of recommendations for potentially fruitful future work. This summary constitutes an overview of the "deliberations" of the Working Group, and it is our hope that the summary clarifies the motivation for the recommended work listed at the end. The summary is organized according to the two aforementioned goals, and the prime topics of discussion appear as subsections under these goals.

2 Goal 1: Survey Status of Underlying Physics and Open Questions

2.1 Theory and Simulation of Coherent Synchrotron Radiation

Enormous progress has been made over the last two years toward simulating the dynamics of electron bunches in bending systems in the presence of co-

herent synchrotron radiation (CSR). Two of the new simulation tools were discussed at length, both of which derive forces at each time step by integrating over the history of the bunch so as to account for retardation. One of them, developed by R. Li of Jefferson Lab, constitutes a self-consistent macroparticle code. The other, described by A. Kabel of DESY, includes a near-self-consistent field generator that drives the orbits of test particles in the bunch.

Although it is straightforward to write down a closed-form Hamiltonian that accounts for CSR by way of the Lienard-Weichert potentials, solving the associated equations of motion is an intricate process. Consequently, the subject of CSR has historically been plagued with debate over which, if any, approximations are valid. One of the products of recent attempts toward self-consistent solutions is an improved understanding of the relative importance of the various terms in the Lienard-Weichert potentials. For example, Li finds that the "noninertial space-charge force" of Carlsten and Raubenheimer is essentially cancelled by the "centrifugal space-charge force" of Talman, and that the residual, and now dominant, terms relate to the centripetal space-charge force.

It remains to benchmark the codes against a comprehensive set of experiments. Several experiments, delineated under Goal 2 below, are planned or in progress. DESY, Jefferson Lab, and CERN/CLIC recently formed a collaboration for benchmarking the two codes against experiments at CLIC/CTF during the coming year.

2.2 Map Methods for Space Charge

The presence of space charge in circular machines vitiates the standard approach of using one-turn maps to calculate the beam dynamics. Instead, space charge necessitates use of relatively small time steps, and the need to track for many turns makes computational efficiency a predominant concern. R. Warnock and J. Ellison presented a computationally efficient Perron-Frobenius discretization of the Vlasov-Fokker-Planck equation. It entails concatenating individual maps for the external forces and the collective forces. They applied the procedure to simulate the impedance-induced instability of the Haissinski equilibrium in rings. Likewise, but in this case for application to linacs, J. Qiang devised a finely time-discretized space-charge map and its parallel-processing implementation into a PIC code based on object-oriented programming. The power of the computational technique became evident in that Qiang was able to simulate the spallation neutron source linac with up to 800 million particles.

2.3   Geometrodynamics

C. Bohn introduced geometrodynamics as a means of studying the evolution of initially nearby trajectories. The essential idea is to devise a metric tensor from the Lagrangian of the system of charged particles for which the associated geodesic equations are the equations of particle motion. Accordingly, the geodesics are themselves particle trajectories, and the behavior of the particle trajectories reflect the properties of the curvilinear manifold in which they are embedded. Bohn applied the methodology to find that the typical time scale for chaotic mixing, corresponding to exponential deviation of initially neighboring chaotic trajectories, in a space-charge-dominated beam is a few plasma periods. Because they populate the Debye tail of the density distribution, these orbits will respond to the influence of external forces and mix initially localized perturbations throughout the bunch, thereby generating irreversible emittance growth. Consequently the mixing time places constraints on methods devised to reverse emittance growth.

2.4   Theory and Simulation of Space Charge in Rings

Growing interest in high-intensity hadron rings, one example being that for the spallation neutron source, necessitates a detailed understanding of the effects of space charge in these rings. This is especially true when high average current is involved, in that residual radioactivity from very small beam loss (of order one part per million) can make hands-on maintenance unsafe. Space charge affords the possibility for lattice periodicities to couple resonantly with collective beam modes and drive them to appreciable amplitudes with attendant halo formation and beam loss. This scenario can present itself even if the initial beam is rms-matched, and because there is a long interaction time in a ring compared to in a linac, it can arise even if space charge is weak.

   The University of Maryland is in the process of building a high-current electron ring (UMER) for experiments on space-charge dynamics. M. Rieser and R. Kishek each gave a talk concerning attempts to understand from first principles how to match a beam to a ring, invoking both analytic theory and simulation of beam dynamics in UMER. Their key points included: depending on the number of turns, the current limit of rings may be less than that of linacs; dispersion from bending magnets may generate irreversible emittance growth; and radial space-charge waves can arise in the beam, yet their dissipation does not necessarily generate emittance growth.

2.5 RF Focusing during Acceleration

Y. Batygin considered the presence of longitudinal rf focusing in guns and injectors. By extrapolating from a thermal-equilibrium distribution, he was able to replicate analytically gross features of the phase space. That his calculations hinge on thermal equilibrium as a starting point, and that his results largely replicate the phase space generated by way of simulation, hint at the presence of fast relaxation to quasi-equilibrium in the systems he considered.

2.6 Electron Cooling of Ion Beams

S. Nagaitsev reviewed the physics of electron cooling of ion beams, as well as experimental verification of the technique. The idea is to couple an electron beam with low transverse temperature to the ion beam having relatively high transverse temperature. The resulting exchange of energy ensuing from Coulomb interactions reduces the transverse emittance of the ion beam. Nagaitsev described techniques for insuring a good match between the electron and ion beams. He also pointed out that if the cooling rate is close to the growth rate of a resistive instability, the ion beam can develop soliton-like structures. In addition, it is possible to overcool a beam and make it unstable, in which case active damping may be required.

2.7 Crystalline Beams

Space charge is generically a source of chaotic behavior and emittance growth. Interestingly, in the limit of a zero-temperature beam, over which space charge has its maximal influence, the beam transitions from a state of chaos to a state of order, a crystalline state. In this limit, the Heisenberg uncertainty principle dictates the emittance. A. Ruggerio summarized the latest ideas and experimental results concerning the formation of crystalline beams, including conditions underlying "phase transitions" between different ordered states. Crystalline beams have been produced in hand-held devices, and transitions between various ordered states have been observed. To date, however, they have not been produced in a large-scale device. Ruggerio summarized an idea that has been evolving over recent years for producing a crystalline beam, namely the use of a circular RFQ combined with cooling from an electron beam or laser beam.

2.8 Nonlinear Local Harmonic Analysis

M. Zeitlin presented a synopsis of theoretical techniques that he and A. Fedorova have recently been developing for application to various problems of nonlinear beam dynamics. Zeitlin's essential message is that numerical-analytical constructions based on nonlinear local harmonic analysis show promise for applications to a wide class of problems of beam dynamics.

3 Goal 2: Identify Sources of, and Cures for, Beam Degradation

3.1 Coherent Synchrotron Radiation

In separate presentations, B. Carlsten and A. Kabel both pointed out that CSR can degrade not only the projected emittance of a beam bunch, but also the slice emittance. The latter degradation is especially important in the context of free-electron lasers, in that it can impede lasing. An x-ray FEL requires both very short bunches (tens of microns) and very low normalized rms emittance (micron-level). Generation of short bunch lengths necessitates the use of bunch compressors comprised of dipole bending magnets, so that CSR is an unwanted byproduct of bunch compression. Therefore, given the ongoing efforts at DESY and SLAC to develop x-ray FELs, the phenomenon requires understanding and control. As described by several speakers at the Workshop, there are a number of experiments that have either been attempted, or are underway or planned, for studying CSR-induced emittance growth and its mitigation. Involved laboratories include Boeing, LANL, Jefferson Lab, ANL/APS, DESY, CERN/CTF, and BNL/ATF. Experiments done to date, such as with the bending systems comprising the Jefferson Lab FEL, have generally been inconclusive concerning the effect of CSR; however, to the extent they can be compared, the results have for the most part been consistent with code predictions. R. Li pointed out that there is generally very good agreement between emittance data taken thus far at CERN/CTF and simulations of the experiment with her code, but that additional parametric studies are warranted. Likewise, A. Kabel's presentation showed that he and his collaborators also obtained fairly good agreement with the same experiment. Nonetheless, predictions between the two codes differ in detail in a manner that should be accessible with parametric studies at CERN/CTF.

P. Emma described techniques that can potentially reverse or minimize CSR-induced emittance growth. They include using the lattice optics to match the beam to the bending system in which CSR is active, or adding optics to dispersively undo the CSR-induced bunch distortion. Bohn pointed

out that these emittance-compensation schemes should be viable as long as they were done beyond the front end of the machine, because otherwise mixing from space charge could inhibit the compensation. The possibility of shielding CSR with a small-aperture vacuum chamber was also discussed.

3.2 Space Charge

Controlling beam degradation from space charge is an ubiquitous problem, and one that is not necessarily limited to nonrelativistic beams. This is especially true in rings because the time frame for the buildup of collective effects is relatively long, so even weak space charge becomes a concern. Nevertheless, it became clear at this Workshop that techniques for beam cooling and concomitant emittance reduction are maturing, such as electron cooling as highlighted by Nagaitsev.

Z. Huang likewise presented a summary of recent thinking related to laser cooling of electron beams in rings. The technique holds promise for achieving very low rms normalized emittances (down to the 10-nm-level), while at the same time providing a source of bright incoherent x-rays.

The question of how best to match a beam to linac and ring lattices remains open. Matching procedures hinging on rms beam properties are not necessarily sufficient for high-average-current machines in which tiny beam loss presents a concern from the standpoint of radiation safety. M. Reiser and R. Kishek both pointed out that the presence of dispersion in rings, combined with possible resonances between collective beam modes and lattice periodicities, make matching in rings especially challenging. Reiser also indicated that, because it is a low-energy machine with a 100-turn beam-containment time, UMER is limited exclusively to studies of space charge. He suggested that it is time to consider an intermediate-energy ring experiment that will permit controlled studies of the interplay between space charge, impedances, wakefields, and lattice resonances.

3.3 Collective Effects in X-Ray FELs

A controversial point concerning the interaction of a bright electron beam with an undulator for self-amplified spontaneous emission of coherent x-rays was that the beam would generate a diamagnetic field that would largely cancel the magnetic field of the undulator and inhibit lasing. P. Musumeci presented work he did in collaboration with J. Rosenzweig toward accurately calculating the induced diamagnetic field. His finding is that the induced field is negligibly low, thereby disspelling the issue.

4   Recommendations for Future Work

As the Workshop unfolded, and as an outcome of focused discussions, the Working Group produced a list of recommendations for future work that seem both timely and potentially fruitful. The list is as follows, the ordering of which reflects no special priority:

• Benchmarking of CSR codes against one another and against experiment needs to continue to completion, a by-product of which should be a clear understanding and delineation of valid approximations to the CSR force.

• Further work is warranted toward the formulation and application of map techniques for rapid, efficient calculation of the influence of collective effects over long time scales. One possibly fruitful activity may be to apply the Perron-Frobenius discretization to the Lienard-Weichert potential with the goal of improving the efficiency of CSR simulations.

• The Working Group felt it appropriate to highlight the utility of object-oriented programming, especially in regard to incorporating map techniques into simulation codes.

• Theoretical tools for calculating evolutionary time scales in particular, and treating nonequilibrium phase-space evolution in general, warrant further development, especially with regard to devising techniques for matching intense beams to linac and ring lattices while both preserving beam quality and minimizing beam losses. As a matter of principle, the Working Group emphasized the need to ensure that efforts to develop theory, simulation, and experiment were combined into a cohesive package.

• The University of Maryland group should make a special effort to connect the experimental program for UMER to ongoing activities across the accelerator community aimed at improving existing high-intensity synchrotrons and storage rings or developing new ones.

• It is timely to start designing an experimental intermediate-energy ring that will permit parametric studies of not only space charge, but also its coupling to impedances, wakefields, and lattice resonances, as well as to consider to what extent related systematic studies can be done with existing machines.

• Though LANL's linac-based beam-halo experiment was beyond the scope of this Working Group's deliberations, the Group nonetheless considers it a relevant and important effort that should contribute toward the overall understanding of space-charge dynamics and how it is influenced by coupling between collective beam modes and lattice periodicities.

• The Working Group feels that topics related to the generation and preservation of crystalline beams merit wider attention in the accelerator community than they are presently being given.

- Further theoretical work toward describing the development, evolution, and influence of localized phase-space structures is warranted, yet special effort should be made toward applying recently developed techniques to solve completely and in detail a specific problem relevant to high-intensity particle beams.